Collapse-type shrinkage characteristics in plantation-grown eucalypts:

I. Correlations of basic density and some structural indices with shrinkage and collapse properties

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Abstract: Collapse-type shrinkage is one of highly refractory drying defects in low-medium density plantation-grown eucalypt wood used as solid wood products. Basic density (BD), microfibril angle (MFA), double fibre cell wall thickness (DWT), proportion of ray parenchyma (RP), unit cell wall shrinkage, total shrinkage and residual collapse, which are associated with collapse-type shrinkage characteristics, were investigated by using simple regression method for three species of collapse-susceptible *Eucalyptus urophyll., E. grandis* and *E. urophylla×E.grandis*, planted at Dong-Men Forest Farm in Guangxi autonomous region, China. The results indicated that: unit cell wall shrinkage had a extremely strong positive correlation with BD, moderately strong positive correlation with DWT, and a weakly or moderately negative correlation with RP and MFA; total shrinkage was positively correlated with BD, DWT and RP and negatively related to MFA, but not able to be predicted ideally by any examined factors alone owing to lower R^2 value ($R^2 \leqslant 0.5712$); residual collapse was negatively correlated with BD and DWT, linearly positively correlated with MFA, and had strongly positive linear correlation with RP. It is concluded that BD can be used as single factor ($R^2 \geqslant 0.9412$) to predicate unit cell wall shrinkage and RP is the relatively sound indicator for predicting residual collapse

Keywords: Basic density; Microfibril angle; Double fibre cell wall thickness; Proportion of ray parenchyma; Unit cell wall shrinkage; Total shrinkage; Residual collapse; Eucalypt plantation

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Introduction

Eucalypt is the most important plantation tree species extensively planted in temperate, subtropical and tropical region outside Australia and ranked in the first in the cultivated forest areas in the world (Wu and Luo 2002a, 2002b; Yin *et al.* 2001). Of all the introduced eucalypt tree species, *Eucalyptus urophylla, E. grandis* and their hybrids are widely popularized and preferred in some countries such as China, Brazil, India, South Africa, etc. owing to their superb growth rate, high productivity and their ability to produce a range of useful forest products such as pulp and paper, round timber, and sawn products (Yin *et al.* 2001; Gominho *et al.* 2001; Malan 1993; Yang 2003). However, previous studies on them have been largely focused on wood properties as a resource for wood fibre (Wu and Luo 2002a, 2002b; Gominho *et al.*2001; Malan 1993; Yang 2003), and few researches were involved in their processing characteristics used as solid products. Only in recent years, there has been considerable interest in growing trees for solid wood products and some preliminary investigation has been performed in their potential for higher value products such as solid wood products, especially appearance-grade sawn timber. However, it is well known that some commercially important eucalypt species, like the above eucalypts, are prone to collapse and honeycomb during drying. Collapse is an abnormal shrinkage encountered in wood of certain tree species in the process of drying. High levels of shrinkage due to collapse causing significant timber degradation were particular evidence in low-medium density eucalypt species (Ilic 1999). At present, it is generally accepted that collapse-type shrinkage including honeycomb is one of the refractory defects in some members of *Eucalyptus* which are used as solid wood products. Although a few studies already had been conducted on mechanisms of collapse (Kauman 1960; Terazawa and Hayashi 1974, 1975; Hayashi and Terazawa 1975a, 1975b, 1975c, 1977; Bariska 1992; Chafe and Ilic 1992b), methods of preventing and relieving of collapse (Chafe 1995, Vermass and Bariska 1995), prediction of collapse (Washusen and Evans 2001, Ilic and Hillis 1986), and wood properties closely related to both collapse and shrinkage (Yang 1991, 2003; Ilic 1999; Washusen *et al.* 2001; Hart 1984; Chafe 1985, 1986a, 1986b, 1987; Chafe and Ilic 1992a), little information was reported on relationship between some anatomical parameters and collapse-type shrinkage properties in eucalypt wood.

Thus, our study is aimed at investigating the relationships of basic density (BD) and three anatomical parameters--Microfibril angle (MFA), double fibre cell wall thickness (DWT) and proportion of ray parenchyma (RP) with shrinkage of unit cell wall, total shrinkage and residual collapse as well as exploring the feasibilities of applying single factor of BD, MFA, DWT and RP to predict shrinkage and collapse properties.

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Materials and methods

Site conditions

The sampling site is located in Dong-Men State Forest Farm in Guangxi Autonomous Region, China, as shown in Table 1.

Table 1. Geographic and climatic conditions in forest sites

Latitude	Longitude	Elevation (m)	Slope	Annual rainfall (mm)
N22.5	E107.5	200	<1	1213
Annual evapo-ration (mm)	Average annual temperature (°C)	Highest tem-perature (°C)	Lowest tempera-ture (°C)	Average annual frost days
1448	21.3	39.2	1.2	3

Collection of sample trees

Fifteen eleven-year-old trees of three kinds of eucalypts (*Eucalyptus urophylla, E. grandis* and *E. urophylla×E. grandis*) planted in same clonal gene pool belonging to Dong-Men Forest Farm established through China-Australia cooperation were selected, immediately one 1.3-m-long billet at diameter at breast height upward was removed from each tree stem after felling, then sealed at two ends with melted waxes, wrapped by plastic films, and finally shipped to Ehime University in Japan so as to be used in immediate experiments. The specific situation on sample trees is shown in Table 2.

Table 2. Growth traits and basic density in sample trees

Species	Num-ber	Mean height density (m)	Mean DBH (cm)	Moisture content in green (%)	Basic density (g·cm^{-3})
E. urophylla	5	27.5	22.8	112.5	0.525
E. grandis	5	25.2	22.5	107.4	0.496
E. urophylla × *E.grandis*	5	28.7	20.2	100.5	0.476

Preparation of specimens

For all the above-mentioned billets, one pith-to-cambium radial board (21×120-mm, tangential (t)×longitudinal (l)) was cut from each billet in south and north direction labeled, respectively. One 21×21×120-mm (t×r×l) sample stick was cut from each of three positions of 10% (innerwood, I), 50% (middlewood, M), and 90% (outwood, O) of the entire radial length for all boards from pith to bark. Finally, 30 sample sticks for every eucalypt species were taken. At first, two end-matched specimens (5×21×10-mm, t×r×l) were cut on each stick, of which one was employed as the determination of microfibril angle (MFA) and the other for both double fibre cell wall thickness (DWT) and proportion of ray parenchyma (RP), then as many 21×21×5-mm(t×r×l) specimens as possible were cut from the remained part of the same stick for the measurement of basic density, shrinkage of unit cell wall, total shrinkage and residual collapse.

Determinations of shrinkage of unit cell wall, total shrinkage and residual collapse

Fifty end-matched specimens (25 at the north and south directions, respectively) at each of three positions (I, M, O), taken from 5 trees of each of 3 kinds of eucalypts, were dried sequentially in a conditioning experimental drying kiln at a dry-bulb temperature (DBT) of 25℃ from green to nominal equilibrium moisture contents (EMC) of 24%, 18%, 12%, 6%, and, finally, 0% in a oven at 103 ± 2℃. Shrinkage and moisture content data were collected at each moisture contents (MC) condition at various states from green to 30% and each EMC at 6 levels of equilibration states from 30% of MC to 0. The dimensions of the specimens at various stages were measured by an electronic caliper with a precision of 0.01 mm. Shrinkage, which, in fact, is named as total one that consists of two parts of normal one below Fiber Saturated Point (FSP) and abnormal one arising from the residual collapse above FSP, was represented as the ratio of the dimensional variation between green and various moisture content (MC) states on the dimension in the saturated state. The mean value of 50 specimens was represented as the shrinkage at the given position of the given species. Collapse, which actually refers to residual one here, was extrapolated to figure out in terms of the following method. Theoretically, for any species wood, shrinkage curve arising from the change of bound water in the cell wall under FSP ought to be very approximate to straight line. Accordingly, as long as several values in shrinkages corresponding to different moisture contents under FSP could be measured for a certain tree species wood, the regression equation for its shrinkage curve could be automatically established using Excel Analysis Software, consequently, the corresponding parameters examined may be determined. In this work, we found that the shrinkage curves in three species of eucalyptus were almost straight lines below about 28% of MC, thereby, the regression equation on them could be expressed as:

$$y_1 = \alpha x + \beta_1 \tag{1}$$

where y_1 represents total shrinkage including residual collapse, x equals MC (≤FSP), α denotes a slope of the line and describes actually unit cell wall shrinkage, and β_1 is intersection to y-axis and expresses the largest total shrinkage at 0% MC. Owing to eucalypt wood being prone-collapse, the total shrinkage resulting from collapse must be larger than normal shrinkage, the value of the difference between the total shrinkage and normal one is generally defined as residual collapse. In order to calculate its magnitude, we assumed that 28 % MC is taken as FSP for the 3 species of eucalypt wood. Thus, the regression equation in normal shrinkage curve which must pass through FSP and parallel to the line expressed by equation (1) could also be rewritten as:

$$y_2 = \alpha x + \beta_2 \tag{2}$$

where y_2 is normal shrinkage at the random MC below FSP, β_2 is intersection to y-axis and the largest normal shrinkage at 0% MC, both x and α are same as that in equation (1). Let x be 28% as FSP, then we have y_2= 0, therefore, β_2 could be determined. The calculated residual collapse should equal the intercept difference value between β_1 and β_2, that is, (β_1- β_2). The process taking average of these values calculated corresponds to the shrinkage.

Measurement of basic density (BD)

Sample mass was measured with an electronic balance (precision 0.0001 g). Volumes were measured by the convenient double weight method (Archimedes principle) in which the sample is first weighed in air and then a second time immersed in water. The force resulting from immersing the sample in water was measured as the difference in mass. The volume was then determined as: Volume=(M_a-M_w)/ρ_w, where, M_a is the mass of the sample in air, M_w is the mass of the sample in water and ρ_w is the density of water at the working temperature.

Determination of microfibril angle (MFA)

All end-matched blocks selected were softened by boiling in the condensable system device with the solution of 90% alcohol to glycerin (1:1, v/v), 25–30 tangential sections of 10–12 μm in thickness were cut with a sliding microtome (Model AO-860), then mounted in the test tube and immersed with Jeffrey's solution (10% nitric acid: 10% chromic acid: water, 1:1:18) for 14-18 h at 40 ℃ until they were entirely macerated into single half fibre wall, which were transferred to a glass slide using a clean stainless steel needle and spread evenly. Thirty MFA were observed and determined randomly under a polarized light microscopy for each sample block, and all measurements from the same locations of 5 trees of every species were averaged to represent the magnitude of the certain location of the given species eucalypt. The same averaging process was also conducted for the following other anatomical parameters.

Determination of double fibre cell wall thickness (DWT) and proportion of ray parenchyma (RP)

Transverse 25-μm thick microsections were cut from the other block matched with that used for measurement of MFA using a sliding microtome. Temporary sections were made on glass slides with glycerine. Microscopic images from the wood cross sections were collected using a Quantimat-750 image analyzer with the image analysis software. Consecutive images were captured from the starting to end of each of the cross sections at radial direction. In each measuring frame the double fibre cell wall thickness (DWT) and the proportion of ray parenchyma (RP), which is defined to the ratio of the total cross sectional area covered by ray parenchyma, were measured and calculated.

Statistic analysis

Simple regression analysis was conducted to examine the relationship of BD, MFA, DWT and RP to unit cell wall shrinkage, total shrinkage and residual collapse with the software of SPSS 12.0.

Results

Average values of BD, three anatomical parameters, unit cell wall shrinkage, total shrinkage and residual collapse properties in *E. urophylla, E. grandis* and *E. urophylla×grandis* are summarized in Table 3. For anatomical features, it can be seen that DWT increases and both MFA and RP decrease from pith toward outer, while so far as shrinkage and collapse properties are concerned, parabola-type radial variation pattern, i.e. low value (I)-peak value (M)-low value (O), was observed on both total shrinkage and residual collapse except the increase in basic density and unit cell wall shrinkage from pith towards outer.

Table 3. Statistical mean values of MFA, DWT, RP, basic density, unit cell wall shrinkage, total shrinkage and residual collapse in 3 positions of 3 eucalypts species

Properties	*E. urophylla*			*E. grandis*			*E. urophylla ×E. grandis*		
	Innerwood	Middlewood	Outwood	Innerwood	Middlewood	Outwood	Innerwood	Middlewood	Outwood
MFA	18.17	15.26	13.16	19.56	15.61	14.28	16.54	13.49	11.36
DWT	6.27	6.55	7.52	5.12	5.59	6.05	6.01	6.15	6.87
RP	18.02	17.09	14.20	17.20	15.43	13.10	17.34	16.03	12.70
BD	0.42	0.48	0.52	0.38	0.46	0.48	0.39	0.46	0.49
α_T	0.252	0.276	0.291	0.242	0.262	0.272	0.241	0.262	0.282
α_R	0.201	0.214	0.226	0.193	0.205	0.214	0.192	0.204	0.217
S_T	9.26	10.25	10.21	8.44	8.88	8.78	8.46	9.24	9.12
S_R	6.08	6.78	6.81	4.91	5.56	5.47	4.89	5.64	5.61
C_T	1.67	1.81	1.12	1.56	1.69	0.95	1.47	1.51	0.87
C_R	0.701	0.74	0.38	0.35	0.65	0.11	0.47	0.59	0.21

Note: MFA=microfibril angle (°); DWT=double fibre cell wall thickness (μm); RP=proportion of ray parenchyma (%); BD =basic density (g·cm^{-3}); α_T =unit cell wall tangential shrinkage (%); α_R=unit cell wall radial shrinkage (%); S_T=total tangential shrinkage (%); S_R=total radial shrinkage (%); C_T=tangential residual collapse (%); C_R=radial residual collapse (%).

Discussions

Relationship of basic density to unit cell wall shrinkage and total shrinkage

Density is widely acknowledged to reflect shrinkage properties. However, it seems to be not entirely satisfactory for low-medium density of eucalypt species. As demonstrated in Figs.1 and 2, the regression analysis of a simple showed that BD was the better predictor for unit cell wall shrinkage (for α_R: R^2 =0.9412; α_T: R^2 =0.9601) than for total shrinkage (for S_R: R^2 =0.5134; S_T: R^2 =0.5145). That is, 94.12% of the variation in α_R and 96.01% of the variation in α_T are due to variation in BD, while BD only accounted for 51.34% of the variation in S_R and 51.45% of the variation in S_T, respectively. In comparison with low to moderate linear relationship of BD to total shrinkage, a very stronger linear association between BD and unit shrinkage indicates that only volumetric changes in cell wall substances play a most important role in unit shrinkage below FSP, while total shrinkage from green to 0% MC reflect the combined varieties in both cell cavity and cell wall volumes. In other words, it is very likely that collapse may occur as long as the shrinkage process accompanies the changes in cell cavity shape. Therefore, it was collapse occurring that led to the increase of total shrinkage including two parts of residual collapse and normal shrinkage and subsequently resulted in inconsistent radial variation trends between unit shrinkage and total shrinkage. i.e. unit cell wall shrinkage increased with increasing BD from pith to bark, while total shrinkage increased from pith outer towards middlewood, then slightly gradually decreased towards outwood with increase of BD along radial direction (Table 3).

Relationship between basic density and residual collapse

Collapse is a type of shrinkage in wood which occurs above the fibre saturation point, i.e. when water is contained within the cell lumens, and is manifested by a bucking of the cell walls and flattening of the lumens. Even if under room-temperature drying state, collapse usually could still occur in some eucalypt species

(Table 3). Similar findings were also reported by some researchers (Ilic 1999; Washusen and Evans 2001). It can be seen from Table 3 that radial variation in total shrinkage and residual collapse shows parabola shape, that is, low values in outwood in spite of high density, high ones in the middlewood and a decline towards the pith. The lower values near the pith than middlewood are caused by the increase of cell wall permeability by compression failures in the cell wall. The reduction of liquid tension by larger permeability made collapse development mitigate. While, compared to middlewood, the extremely lower values in outwood may be inferred to be closely related to its higher permeability in sapwood and low percentage of RP. As presented in Fig. 3, although there is a significantly ($P<0.05$) negatively linear relationship between residual collapse and basic density, only less than 50% of variation in residual collapse was explained by BD. This shows that BD is not a good predictor in residual collapse because some more important anatomical characteristics are very likely to participate in the formation of residual collapse so as to weaken greatly the effect of BD on it.

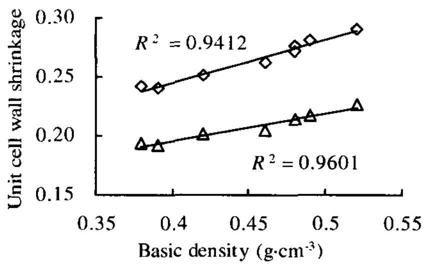

Fig. 1 Unit cell wall shrinkage plotted against basic density of planted eucalypt

◇: Unit cell wall tangential shrinkage; △: Unit cell wall radial shrinkage

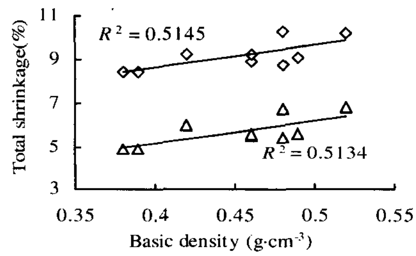

Fig. 2 Total shrinkage plotted against basic density of eucalypt

◇: Total tangential shrinkage; △: Total radial shrinkage

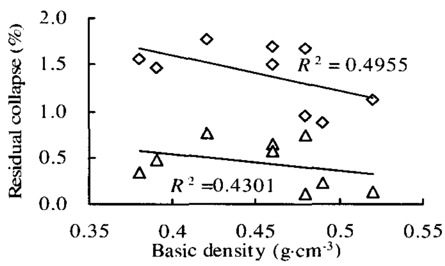

Fig. 3 Residual collapse plotted against basic density of eucalypt

◇: Tangential residual collapse; △: Radial residual collapse

Relationship of anatomical characteristics with unit cell wall shrinkage and total shrinkage

There is a significant positive linear relationship between unit cell wall shrinkage and DWT and a moderately negative linear relationship of unit cell wall shrinkage to MFA (Fig. 4). DWT and MFA account for more than 60% of the variation in unit cell wall shrinkage, and their variations are higher and correlations are more significant than RP. This shows that DWT and MFA are more relatively suitable for indicators of unit cell wall shrinkage than RP. In fact, this finding agrees well with the effect of BD on unit cell wall shrinkage. It is well known that MFA has a great effect on shrinkage properties (Kollmann and Cote 1968; Panshin and Zeeuw 1980), as usual, the greater the MFA, the smaller the transverse shrinkage in cell walls substance. However, DWT and RP have positive correlation with total shrinkage, while the reverse is true for MFA (Fig. 5). Compared to 3 anatomical parameters regressed on unit cell wall shrinkage, all corresponding coefficients of determination in 3 simple regression equations for total shrinkage are lower, implying any factor alone in 3 anatomical indices can not be regarded as reasonable predictor for total shrinkage. This appears to be demonstrated that shrinkage behaviors in collapse-prone eucalypt are very complicated and some thinner-wall cells such as ray parenchyma very possibly participate in shrinkage process, which result in abnormal shrinkage in eucalypt wood. Interestingly, we also found that RP was negatively correlated with unit cell wall shrinkage and positively correlated with total shrinkage (Figs. 4 and 5). This finding indicated that RP played different roles in shrinkage process, i.e. total shrinkage accompanying collapse increases and normal shrinkage decreases with the increase of RP because normal shrinkage is mainly closely related to the contents of cell wall substances, which decline with the increase of RP.

Relationship between anatomical characteristics and residual collapse

As demonstrated in Fig. 6, it has been found that DWT is negatively linearly related to residual collapse, regardless of C_R or C_T, and RP is strongly linearly positively correlated with residual collapse, and explains as high as 74.54% to 81.7% of variation in residual collapse, while MFA and DWT account for only 18.39% to 50.09% of the variation in residual collapse, indicating RP alone may be applied to the prediction of magnitude of residual collapse in collapse-prone eucalypts. This also has demonstrated that collapse is extremely complicated shrinkage phenomena and involved in types and numbers of anatomical elements participating in the formation of collapse. Similar to total shrinkage, patterns in radial variation in residual collapse also take on parabola-type one from pith towards outer (Table 3). This finding further confirmed the hypothesis provided by Hart (1984) who advocated that RP could play an important role in the formation in collapse. It is generally thought that providing one of the following three requirements, i.e. impermeability, water saturation of the cell lumen and comparatively thin cell walls, is contented, collapse may probably occurs in some species. Ray parenchyma cells in eucalypt wood can be rather easier to meet any requirements in collapse. Notwithstanding, collapse would less likely to occur in the relatively thick cell walls because the wood would be stronger in compression perpendicular to the grain. Kauman (1964) found that the tendency for collapse to be smaller in the radial than in the tangential direction is attributed to restraint offered by rays, a finding consistent with that shown in Table 3. Bariska (1992) reported the buckling of the ray parenchyma cells in *E. macarthurii* and *E. elata* was observed along the long axis, this has been expected due to the overall radial collapse shrinkage of the stems. It was reported by Hattori *et al.* (1979) and Kanagawa *et al.* (1978) that not only the

increment in external shrinkage resulted from the increase in the number of collapsed ray cells within high moisture content range above the fibre saturation point, but also deformed cells in collapsed samples were observed mainly in ray parenchyma. This has further shown that, to some extent, the ray cells in collapse susceptible species could make the greater contribution to the generation of wood collapse and would be regarded as one of main indicators of the cell-collapse intensity. However, In particular, owing to variation and complication of anatomical structure in collapse-prone species wood, so far no consistent conclusions have been obtained on effect of anatomical features on shrinkage properties. Chafe *et al.* (1992) concluded based on the previous findings reviewed that there were no relationship between collapse and proportions of fibres, axial parenchyma, vessels, vessel dimensions or rays in *E. regnans*. Bisset and Ellwood (1951) found that collapse was negatively related to fibre wall thickness across a growth ring. Ilic and Hillis (1984) revealed that collapse was related to the proportion of fibres with specific cell wall thickness. Nasroun *et al* (1998) found that the most important anatomical properties affecting shrinkage were vessel diameter, diameter of parenchyma cells, lumen fraction and diameter of fiber lumen. Bello (1997) reported some factors influencing shrinkage and characteristics were probably fibre cavity diameter, fiber diameter and cell wall proportion. Yang *et al.* (2003) observed that MFA was not significantly correlated with collapse, significantly and negatively correlated with only tangential shrinkage in *E. globules*. Thus, it is necessary to investigate further systematically relationship between anatomical characteristics and shrinkage properties in collapse-susceptible plantation-grown eucalypt wood.

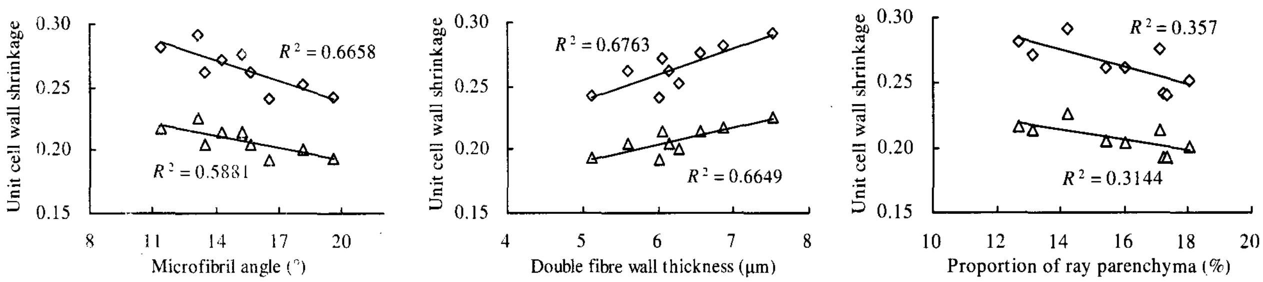

Fig. 4 Unit cell wall shrinkage plotted against anatomical features of planted eucalypt
◇: Unit cell wall tangential shrinkage;△: Unit cell wall radial shrinkage

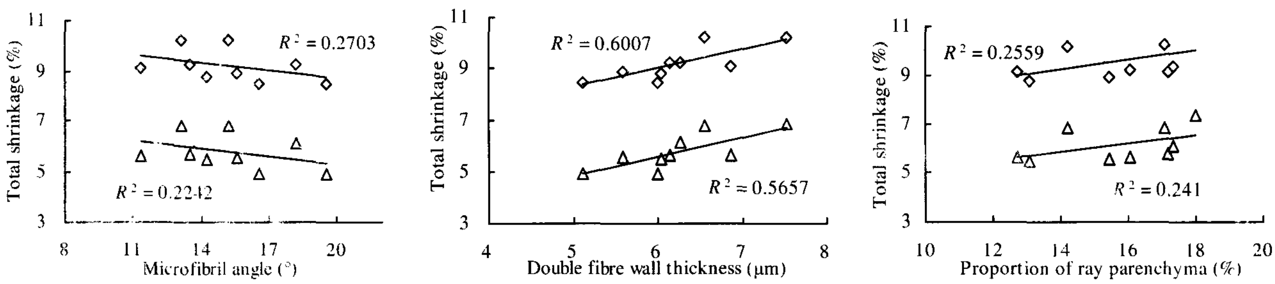

Fig. 5 Total shrinkage plotted against anatomical features of planted eucalypt
◇: Total tangential shrinkage; △: Total radial shrinkage

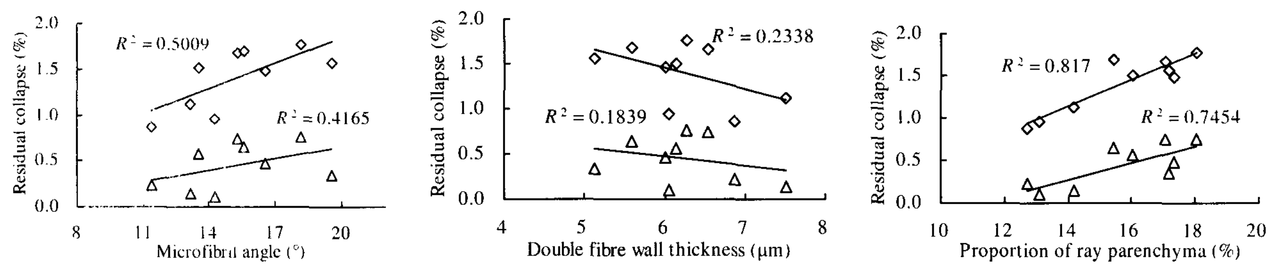

Fig. 6 Residual collapse plotted against anatomical features of planted eucalypt
◇: Tangential residual collapse; △: Radial residual collapse

Conclusions

Based on simple linear regression analysis between basic density and anatomical features (DWT, MFA and RP) and shrinkage characteristics (unit cell wall shrinkage, total shrinkage and residual collapse) and analysis of radial variation in the parameters examined, the following conclusions could be drawn for low-medium density plantation-grown eucalypt wood:

Basic density (BD), double fibre cell wall thickness (DWT) and unit cell wall shrinkage increase and microfibfil angle (MFA) and proportion of ray parenchyma (RP) decrease from

pith towards bark, while total shrinkage and residual collapse exhibit similar parabola-type radial variation patterns, i.e. low value (I)-peak value (M)-low value (O).

Unit cell wall shrinkage was strongly linearly positively correlated with BD, moderately to strongly linearly correlated with DWT, and weakly to moderately negatively linearly correlated with RP and MFA, thus it could be well predicted by BD. BD is regarded as the first indictor and DWT is regarded as the second one for predicting unit cell wall shrinkage.

Total shrinkage was linearly positively correlated with BD, DWT and RP, and linearly negatively correlated with MFA, but was not capable of being predicted in terms of any single factor of the above four parameters examined.

Residual collapse was moderately to strongly positively correlated with MFA and RP, weakly linearly negatively correlated with BD and DWT. RP was the relatively sound indicator for predicting residual collapse.

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·References

Bariska, M.1992. Collapse phenomenon in eucalypts [J]. Wood Sci Technol., **26**: 165–179.

Bello, E.D. 1997. Specific gravity-volumetric shrinkage relationship of some Philippine wood species [J]. FPRDI Journal, **23**: 15–30.

Bisset, I.J.W., Ellwood, E.L. 1951. The relation of differential collapse and shrinkage to wood anatomy in *Eucalyptus regnans* FvM and *Eucalyptus gigantean* Hook F [J]. Aust. J. Appl. Sci., **2**: 175–183.

Chafe, S.C. 1985. The distribution and interrelationship of collapse, volumetric shrinkage, moisture content and density in trees of *Eucalyptus regnans* F.Muell [J]. Wood Sci. Technol., **19**: 329–345.

Chafe, S.C. 1986a. Collapse, volumetric shrinkage, specific gravity and extractives in Eucalyptus and other species. Part 1: The shrinkage/specific gravity ratio [J]. Wood Sci. Technol., **20**: 293–307.

Chafe, S.C. 1986b. Radial variation of collapse, volumetric shrinkage, moisture content and density in *Eucalyptus regnans* F.Muell [J]. Wood Sci. Technol., **20**: 253–262.

Chafe, S.C. 1987. Collapse, volumetric shrinkage, specific gravity and extractives in Eucalyptus and other species. Part 2: The influence of wood extractives [J]. Wood Sci. Technol., **21**: 27–41.

Chafe, S.C. 1995. Preheating and continuous and intermittent drying in boards of *Eucalyptus regnans* F. Muell. Ⅰ. Effect on internal checking, shrinkage and collapse [J]. Holzforschung, **49**: 227–233.

Chafe, S.C., Barnacle, J.E., Hunter, A.J., Northway, R.L., Rosa, A.N. 1992. Collapse: an introduction [C]. CSIRO, Div. of Forest Products, Melbourne, Australia, pp1–9.

Chafe, S.C., Ilic, J. 1992a. Shrinkage and collapse in thin sections and blocks of Tasmanian mountain ash regrowth. Part 2: The R-ratio and changes in cell lumen volume [J]. Wood Sci. Technol., **26**: 181–187.

Chafe, S.C., Ilic, J. 1992b. Shrinkage and collapse in thin sections and blocks of Tasmanian mountain ash regrowth. Part 3: Collapse [J]. Wood Sci. Technol., **26**: 343–351.

Gominho, J., Figueira, J., Rodrigues, J.C., Pereira, H. 2001. Within-tree variation of heartwood, extractives and wood density in the eucalypt hybrid urograndis (*Eucalyptus grandis* ×*E. urophylla*) [J]. Wood Fiber Sci., **33**: 3–8.

Hart, C.A. 1984. Relative humidity, EMC, and collapse shrinkage in wood [J]. Forest Prod. J., **34**: 45–54.

Hattori, Y., Kanagawa, Y., Terazawa, S. 1979. Progress of shrinkage in wood Ⅲ.An observation of the development of the cell-collapse by the freeze-drying method [J]. Mokuzai Gakkaishi, **25**: 191–196.

Hayashi, K., Terazawa, S. 1975a. Studies on cell-collapse of water-saturated balsa wood Ⅲ. The effect of the tensile stress on the collapse intensity [J]. Mokuzai Gakkaishi, **21**: 278–282.

Hayashi, K., Terazawa, S. 1975b. Mechanism on collapse occurring in wood drying Ⅰ [J]. Mokuzai Kogyo, **30**: 2–12.

Hayashi, K., Terazawa, S. 1975c. Mechanism on collapse occurring in wood drying. Ⅱ [J]. Mokuzai Kogyo, **30**: 11–15.

Hayashi, K., Terazawa, S. 1977. Studies on cell-collapse of water-saturated balsa wood. Ⅴ. Estimation of magnitude of liquid tension produced by drying [J]. Mokuzai Gakkaishi, **23**: 30–34.

Ilic, J. 1999. Shrinkage-related degrade and its association with some physical properties in *Eucalyptus regnans* F Muell [J]. Wood Sci. Technol., **33**: 425–437.

Ilic, J., Hillis, W.E. 1984. Association of wood anatomy with collapse in ash type eucalypts [C]. In: Proc Pac Reg Wood Anatomy Conf, Tsukuba, Japan, pp19–21.

Ilic, J., Hillis, W.E. 1986. Prediction of collapse in dried eucalypt wood [J]. Holzforschung, **40**: 109–112.

Kollmann, F.P., Cote, W.A. 1968. Principles of wood science and technology. Ⅰ. Solid wood [M]. Springer, Berlin Heidelberg New York, pp18–52.

Kanagawa, Y., Hattori, Y. 1978. Progress of shrinkage in wood. Ⅰ.[J]. Mokuzai Gakkaishi, **24**: 441–446.

Kauman, W.G. 1960. Contributions to the theory of cell collapse in wood: Investigations with *Eucalyptus regnans* [J]. Aust. J. Appl. Sci., **1**: 122–145.

Kauman, W.G. 1964. Cell collapse in wood [J]. Holz Roh Werkst, **22**: 183–196.

Malan, F.S. 1993. The wood properties and qualities of three South African-grown eucalypt hybrids [J]. South Afr. For. J., **167**: 35–44.

Nasroun, T.H., Al-shahrani, T.S.S. 1998. The relationship between anatomical properties of wood and some of its physical properties (2) The relationship between anatomical properties and shrinkage [J]. Arab Gulf Journal of Scientific Research, **16**: 183–206.

Panshin, A.J., de Zeeuw. 1980. Textbook of wood technology, 4th edn, Vol 1[M]. New York: McGraw-Hill, pp93–124.

Terazawa, S., Hayashi, K. 1974. Studies on cell-collapse of water-saturated balsa wood. Ⅰ. Relation of shrinkage process and moisture distribution to cell-collapse mechanism [J]. Mokuzai Gakkaishi, **20**: 306–312.

Terazawa, S., Hayashi, K. 1975d. Mechanism on collapse occurring in wood drying Ⅲ [J]. Mokuzai Kogyo, **30**: 2–14.

Vermass, H.F., Bariska, M. 1995. Collapse during low temperature drying of *Eucalyptus grandis* W Hill and *Pinus sylvestris* L. [J]. Holzforschung und Holzverwertung, **47**: 35–40.

Washusen, R., Ades, P., Evans, R., Ilic, J., Vinden, P. 2001. Relationships between density, shrinkage, extractives content and microfibfil angle in tension wood from three provenances of 10-year-old *Eucalyptus globules* Labill [J]. Holzforschung, **55**: 176–182.

Washusen, R., Evans, R. 2001. Prediction of wood tangential shrinkage from cellulose crystallite width and density in one 111-year-old tree of *Eucalyptus globulues* Labill [J]. Australian Forestry, **64**: 123–126.

Wilkes, J., Wilkins, A.P. 1987. Anatomy of collapse in *Eucalyptus* spp. [J]. IAWA Bull, **8**: 291–295.

Wu Yiqiang, Luo Jianju. 2000a. Studies on variation of anatomical properties o f the clones of *Eucalyptus grandis* within a tree and among trees [J]. Journal of Central South Forestry University, **20**: 34–41. (in Chinese)

Wu Yiqiang, Luo Jianju. 2000b. Studies on growth traits and wood properties of the clones of *Eucalyptus grandis* and selection of preponderant clones [J]. Journal of Central South Forestry University, **20**: 42–48. (in Chinese)

Yang, J.L. 1991 Relationship between microdensity and collapse in *Eucalyptus regnans* F Muell [J]. J Inst Wood Sci, **14**: 78–82.

Yang, J.L. 2003. Interrelationships between shrinkage properties, microfibril angle, and cellulose crystallite width in 10-year-old *Eucalyptus globules* [J]. N. Z. J. For. Sci., **33**: 47–61.

Yin Yafang, Jiang Xiaomei, Lu Jianxiong, Su Hongze. 2001. Status of resources and wood utilization of eucalyptus plantation in China [J]. China Wood Industry, **15**: 3–5. (in Chinese)